Final Report:

"Parallel Coupled PBL-Hydrology Modeling Techniques for Assimilating Remote Sensing Data into a Mesoscale Meteorology Model"

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Summary

This report documents the Georgia Tech contribution to the project "Assimilation of Remote-Sensing Data into a Coupled Hydrological/Meteorological Modeling System Using Parallel Techniques", funded under EPA Grant Number R825210 from the U.S. Environmental Protection Agency to MCNC. The project was selected in a competitive RFA under the 1996 STAR research area 96-NCERQA-8c. High Performance Computing – Data Access and Analysis Techniques.

The overarching goal of this research has been the incorporation of remote sensing data into a coupled hydrological/meteorological modeling system through the application of HPC parallel techniques in order to improve the predictive capabilities and practical usability of the system and reduce the uncertainties associated with using models for environmental risk assessments. By leveraging the efforts of other related projects and extending the performance period via two no-cost extensions on the Prime contract as well as this subcontract, we have been able to meet virtually every science and technological goal outlined in the original proposal, in addition to supporting two Masters theses and one Ph.D. dissertation in Georgia Tech's School of Civil and Environmental Engineering. In accordance with the goals of the project, we have applied HPC parallel techniques to develop a coupled hydrological/meteorological modeling system capable of assimilating remotely sensed precipitation and radiation data. The HPC parallel techniques improve both the predictive capabilities and practical usability of the system, by allowing a fine scale surface hydrology model (Sparse-TOPLATS) to be coupled to a meso-scale meteorology model (MM5V3) to improve the representation of sub-grid scale heterogeneities that are responsible for significant errors in both model(s) and thereby reduce the uncertainties associated with using models for environmental risk assessments. Both inter and intra-program HPC parallel computational techniques have been incorporated to improve the approach to data assimilation and coupling of the models on temporal and spatial scales.

As described in Section 2, the design of the Sparse-TOPLATS model reduces simulations that once took approximately 5 hours to 5 minutes (on a single processor), by applying concepts of hydrologic similarity with appropriate discretization of topographic and meteorological inputs. Open-MP parallelism further reduces the execution time on shared memory multiprocessor systems. This design, in addition to a PVM-based "peer-to-peer" coupling strategy described in Section 3, allows for coupling models with disparate spatial and temporal discretizations, in three distinct modes: 1-way, 1.5-way, and 2-way. The 1- and 1.5-way modes are useful particularly for retrospective simulations in which all or part of the required data for one of the models is available from reliable sources, two of which might be NEXRAD precipitation data and GOES radiation data, as described in Section 4. Two-way coupling is required for forecasting applications, and is useful for examining feedbacks in the land-atmosphere system.

One-dimensional (1-D) coupled simulations described in Section 5 indicate that the coupling is important for atmospheric boundary layer development, although large-scale dynamics also play an important role. In Section 6, 3-D coupled results for a large domain in the Houston-Galveston region indicate that high-resolution land surface modeling can be important for resolving complex urban heat island/sea breeze interactions, and that the assimilation of remotely sensed radiation is critical for accurate energy balance simulation.

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1: Introduction

This report documents the Georgia Tech contribution to the project "Assimilation of Remote-Sensing Data into a Coupled Hydrological/Meteorological Modeling System Using Parallel Techniques", funded under EPA Grant Number R825210 from the U.S. Environmental Protection Agency to MCNC. The project was selected in a competitive RFA under the 1996 STAR research area 96-NCERQA-8c. High Performance Computing – Data Access and Analysis Techniques.

The overarching goal of this research has been the incorporation of remote sensing data into a coupled hydrological/meteorological modeling system through the application of HPC parallel techniques in order to improve the predictive capabilities and practical usability of the system and reduce the uncertainties associated with using models for environmental risk assessments. To meet this goal, we have coupled a fine scale surface hydrology model (Sparse-TOPLATS) with a mesoscale meteorology model (MM5V3) to try to improve the representation of sub-grid scale heterogeneities that are responsible for significant errors in both model(s). We have also incorporated remote sensing data into the coupled modeling system, targeting critical known predictive deficiencies, including precipitation and insolation. Further, inter and intra-program HPC parallel computational techniques have been incorporated to improve the approach to data assimilation and coupling of the models on temporal and spatial scales. The first application of the techniques developed as part of the research takes advantage of the extensive data sets available from the 1994 Little Washita, Oklahoma field experiments. Application to other independent datasets and study periods, including sites in North Carolina and Texas, demonstrates the potential for scaling up and broader applicability. The hydrology model demonstrates topographically based, lateral land-surface water transport, which is valuable for cross-media environmental assessments, particularly when precipitation may contain potential environmental contaminants.

By leveraging the efforts of other related projects and extending the performance period via two no-cost extensions on the Prime contract as well as this subcontract, we have been able to meet virtually every science and technological goal outlined in the original proposal, as listed below:

1.1 Project Goals

Year 1

- Incorporate TOPLATS into EDSS.
- Develop/test Parallel Programming Libraries.
- Develop assimilation strategies for NEXRAD and GOES data.
- Design model coupling strategies.
- Perform 1D coupled TOPLATS/PBL model simulations and compare against LES results.

Year 2

- Develop/test Parallel Programming Libraries.
- Develop additional assimilation strategies as needed.
- Couple TOPLATS model to MM5V1 in "one way" mode.

- Perform "one-way" coupled runs to determine optimal assimilation strategies.
- Evaluate runs against baseline MM5V1 simulations.
- Evaluate topographically induced land-surface lateral water transport.
- Assess strengths and weaknesses of one-way approach.

Year 3

- Refine parallel communication methods.
- Couple TOPLATS to MM5V1 in "two way" mode.
- Perform "two-way" coupled runs for optimal assimilation strategies.
- Evaluate runs against baseline MM5V1 simulations.
- Evaluate land-surface lateral water transport.
- Assess strengths and weaknesses of two-way approach.

This report summarizes the science basis, methods, and results of the coupled hydrological/meteorological modeling system development. Section 2 describes the Sparse-TOPLATS design and presents results showing the computational performance as well as the performance of the model against data for various sites. Section 3 describes the Sparse-TOPLATS/MM5 coupling design, including the I/O and HPC parallel implementation. The assimilation of remotely sensed rainfall and insolation are discussed in Section 4. Section 5 gives results of 1-D coupled simulations used to evaluate the coupling design and impact of a high-resolution hydrological model on the atmospheric boundary layer. The 3-D coupled results for two case studies are presented in the following section. Finally, conclusions and recommendations for future study are given in the final section.

2: Sparse-TOPLATS Design

Year 1 of the project focused on the re-design of the original TOPLATS model (Famiglietti and Wood, 1994; Peters-Lidard et al., 1997; 1998) to incorporate the OpenMP enabled Models-3 I/O API (Coats et al., 1999), into TOPLATS in order to support parallel processing. This incorporation also included initial designs for assimilating NEXRAD and GOES data as well as strategies for coupling to the MM5 model. The final designs for data assimilation and MM5 coupling will be described in Sections 3 and 4, respectively. The initial design is summarized in an AMS preprint (Peters-Lidard et al., 1999), and the final design is the subject of a manuscript in preparation (Peters-Lidard et al., 2002). Below, the major aspects of the design are discussed.

2.1 Design Concepts

A survey of Land Surface Parameterizations (LSPs) or Soil-Vegetation-Atmosphere Transfer Schemes (SVATS) used for Numerical Weather Prediction (NWP) or Air Quality applications reveals that LSPs are typically applied for convenience at the spatial and temporal scales of their host models without consideration of the inherent spatial and temporal scales of hydrological processes. However, due to heterogeneities of the land surface (topography, soil, and vegetation) and the time scale of moisture transport, the natural spatial scale for hydrology is 100 meters or less, while the temporal scale is on the order of minutes to hours. Meteorological meso-scales are quite different, on the order of 10's of kilometers in the horizontal together with time scales on the order of 10's of seconds. Thus, physically, there is no reason to apply a hydrological model at a 10km or larger grid resolution and a 60 second or smaller temporal resolution. In addition, the fundamental control on water flow is gravity, which leads to the fundamental unit of hydrology as the catchment (or watershed). These concepts are missing from the current generation of LSPs, and therefore modelers are unable to verify their water budgets by taking advantage of the best available data for that purpose—streamflow data. Therefore, two requirements drove the design of the Sparse-TOPLATS model:

1.) Must be efficient in its computations and operate at its own spatial and temporal scales; and

2.) The coupling between the TOPLATS and MM5 must consider the problem of disaggregation and aggregation of fluxes of momentum, heat and mass

In order to meet requirement 1) above, a scientific evaluation of the important spatial and temporal scales for calculating land surface hydrological fluxes and states was undertaken, as described in the next section.

2.2 Science Basis

Attempting to employ a 30m spatial resolution LSP over a mesoscale modeling domain is problematic due to data and computational constraints as well as the flux aggregation problem. Since TOPLATS structures its computations as a hierarchy, we found that we can define grid cells, or "sparse elements", which are "hydrologically similar" using the following five properties (for relatively flat areas):

1. meteorology;
2. soils-topographic index;
3. land cover type;
4. soil type; and
5. catchment basin.

Cells exhibiting identical properties can be reduced computationally to sparse elements, which have multiplicity > 1. Therefore by sorting cells on the key quintuple above, we may perform computations on unique sparse elements and utilize their multiplicities in the aggregation of results. Although the first two of these properties (meteorology and the soils-topographic index) vary continuously, we have found that appropriate discretization of both yields efficiency as well as accuracy in subsequent computations.

2.2.1 Meteorology Discretization

Our discretization process for meteorological forcings involves their interpolation to a common grid. This process is not trivial, since "meteorology" may be derived from one or more of the following sources:

1. Mesoscale model output, as represented by the (12-km proposed) MM5 grid;
2. Remotely sensed data, as represented by the (approximately 4-km) NEXRAD or GOES grids;
3. Data from surface-observation sites; or
4. Data from upper-air (rawinsonde) sites.

2.2.2 Soils-Topographic Index Discretization

The soils-topographic index is our surrogate for topography in the model. We have tested various discretizations of the soils-topographic index and found that by choosing as little as 20 bins from the cumulative distribution function, we can obtain reasonably accurate representation of model fluxes and states (see Section 2.3. below). By taking advantage of similarities in hydrological behavior, a new version of the TOPMODEL-based Land Atmosphrere Transfer Scheme (TOPLATS; Famiglietti and Wood, 1994; Peters-Lidard et al., 1997; 1998), can be applied with computational performance approaching that of a much simpler LSP while retaining the complex soil-vegetation-topographical details of the original TOPLATS. Because the new model makes use of sparse-matrix operations for aggregation and disaggregation, it has been named Sparse-TOPLATS.

2.3 Application to the Little Washita 1994 Experiment

The original TOPLATS solves surface water and energy balances as well as 1-D soil water and heat diffusion on a fine-resolution computational grid where each grid element has a unique meteorology, topography, land cover, soil texture, and watershed. TOPLATS represents the effect of watershed-scale redistribution of soil water via a drainage index known as the soils-topographic index. The spatial scale of the model application is determined both by the availability of data and the inherent scales of hydrological processes. When applied to the Little Washita August 1994 IOP, the model is run at a 30 m spatial discretization with an hourly time step.

The Sparse-TOPLATS model was run offline to simulate the water and energy balance for the Little Washita Watershed during the period August 18-23, 1994, corresponding to the NASA/USDA Washita '94 IOP. Below, we illustrate the performance improvements relative to the original TOPLATS model as well as an analysis of flux and soil moisture errors due to the discretization process.

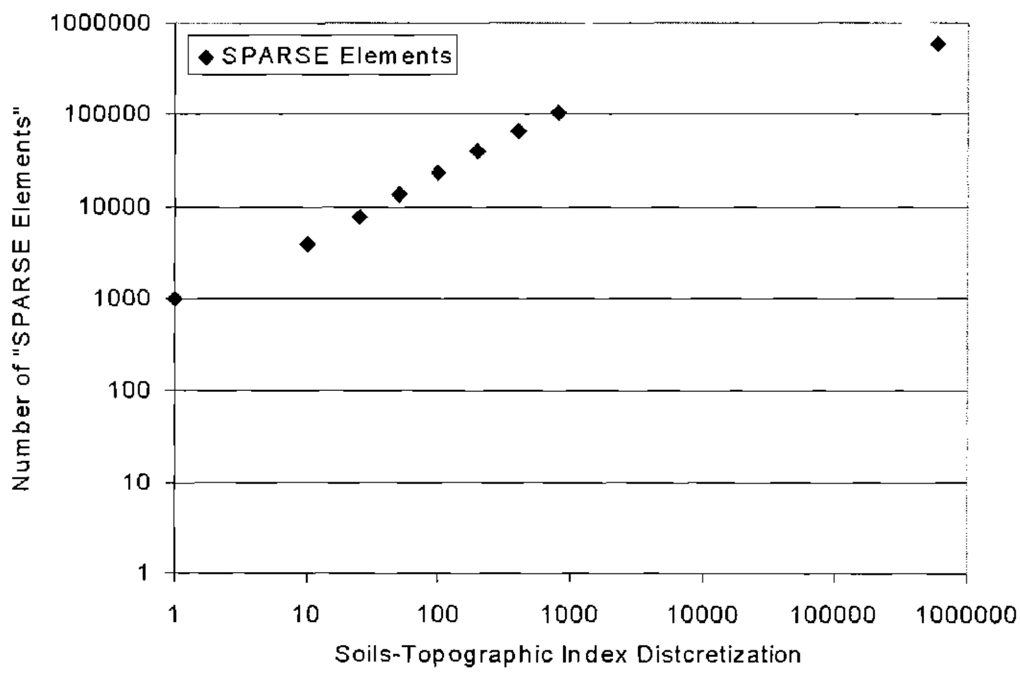


Figure 1. Number of SPARSE elements versus soils-topographic index discretization.

Figure 1 illustrates the number of sparse elements versus soils-topographic index discretization. This figure shows that large enough multiplicities are obtained so as to significantly reduce the computational burden associated with computation and aggregation procedures. Figures 2, 3, and 4 illustrate corresponding improvements in memory, disk space, and CPU time.

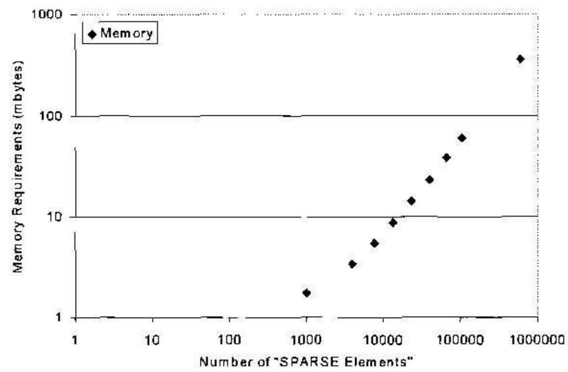


Figure 2. Reduction in memory vs. sparse elements.

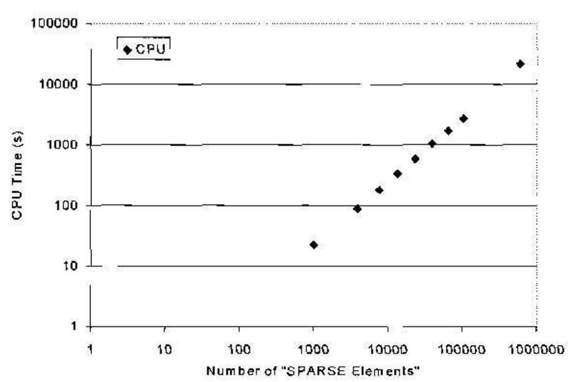


Figure 3. Reduction in CPU time vs. sparse elements. CPU time measured on a single 180MHz R10000 processor on an SGI Origin 200 system.

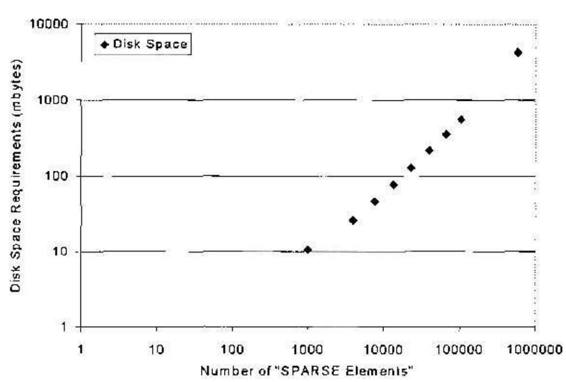


Figure 4. Reduction in disk space vs. sparse elements.

Figures 5 and 6 illustrate that Sparse-TOPLATS yields little loss of accuracy in latent heat flux (LE) (<10 W m-2) and 5 cm soil moisture (< 5%) as compared to the original model. However, the figures illustrate that the soils-topographic index discretization is important, since errors obtained using the mean value (or a discretization of one) are in excess of 40 Wm-2 for LE during midday and more than 20% for 5-cm soil moisture.

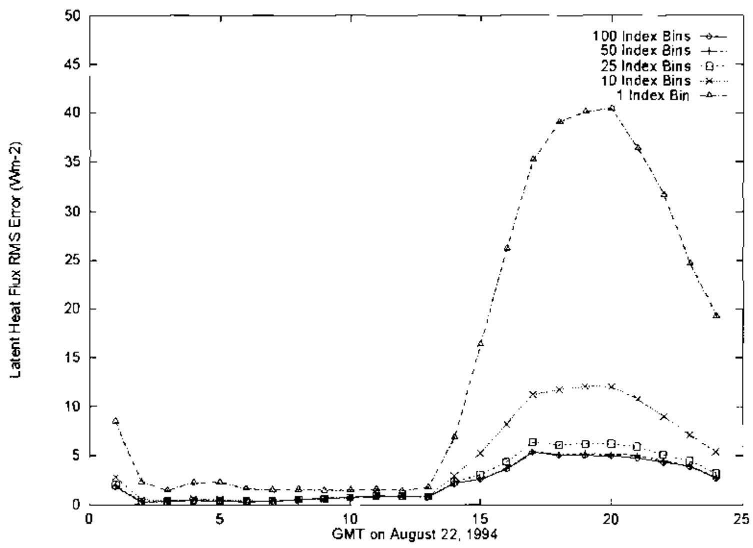


Figure 5. RMS Error in latent heat flux due to topographic index discretization. Acceptable levels of error are obtained with only 25 index bins.

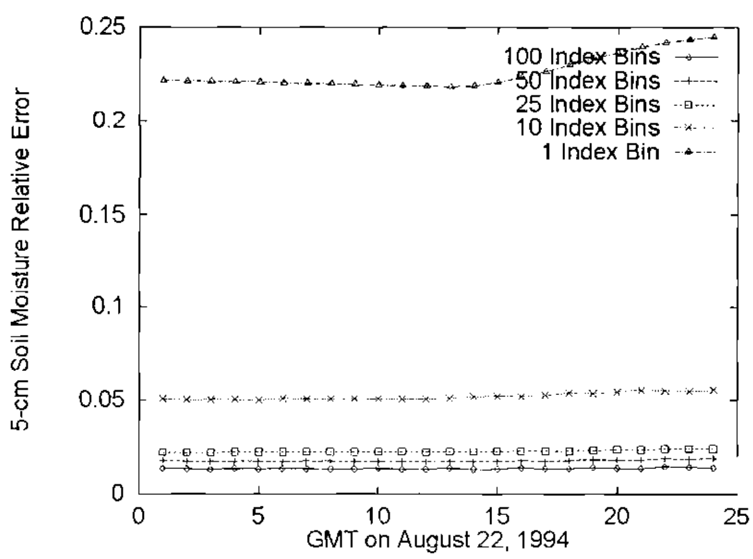


Figure 6. Relative error for soil moisture due to topographic index discretization. As with latent heat flux, 25 bins seem to provide an acceptable level of error.

3: Sparse-TOPLATS/MM5 Coupling Design

Year 2 of the project focused on the design of a model-coupling interface approach which consists of: (1) a drop-in MM5V2 (Grell et al., 1995) module MCPL() (Coats, 1998b) that provides selective direct access to MM5 outputs variable-by-variable; (2) a module which reads Sparse-TOPLATS fluxes and aggregates them for use by MM5; (3) drop-in Sparse-TOPLATS modules that perform mirror functions (output to MM5 and disaggregation of MM5 output for use by Sparse-TOPLATS); (4) a Parallel Virtual Machine (PVM) (Geist et al., 1994; PVM, 1998)-based interface (Coats et al., 1999) that allows the two models to coordinate with each other and exchange data, while retaining their own fundamental spatio-temporal physical and computational characteristics. The initial coupling interface is summarized in two AMS preprints (McHenry et al., 1999, Coats et al., 1999), and the final coupled model results are the subject of a manuscript in preparation (Peters-Lidard et al., 2002). Below, the major aspects of the coupling design are discussed.

3.1 Design Concepts

As stated above, we have sought a coupling interface that allows the two models to coordinate with each other and exchange data, while retaining their own fundamental spatio-temporal physical and computational characteristics. Rigorous and efficient aggregation, disaggregation and communication of flows between the models are central to this issue.

3.1.1 Aggregation

In principle, an LSP would provide fluxes of heat, moisture and momentum to the host model. Various authors have examined this issue, mostly from the perspective of estimating "effective parameters" for LSP's that could be utilized in coarse-resolution atmospheric models, e.g. Mahrt (1987), Mason (1988), Shuttleworth (1988), Claussen (1991), Klassen (1992) and Blyth et al. (1993). Our approach to the LSP problem is to allow the Sparse-TOPLATS to run with geometry based on the catchment and detached from but geo-registered with the host model. We can then utilize the spatio-temporal statistics of the fluxes in their aggregation to the host model resolution.

Simple averaging of scalar fluxes (heat and moisture, as well as potentially other chemical constituents) ensures mass conservation, and is the approach we have chosen. However, in the case of momentum, a simple average of "local" shear stresses calculated by Sparse-TOPLATS would not resolve the additional shear stress generated at internal boundary layer boundaries or due to form drag. This is a critical theoretical issue that limits our ability to couple fine-scale LSPs to coarser-resolution atmospheric models. The work of Albertson et al, (2000) and Mahrt () suggests that it may be possible to parameterize the additional shear stress due to these effects, but theoretical work in this area was determined to be beyond the scope of the project. Therefore, in this implementation, only the scalar fluxes from TOPLATS are coupled to MM5.

3.1.2 Disaggregation

The problem of disaggregation of host model output fluxes to drive the LSP must be carefully considered in addition to the aggregation problem. Key model output for the LSP includes radiative fluxes such as downward shortwave and downwelling longwave, precipitation, winds, and air temperature and humidity. It is well-known that even relatively fine resolution mesoscale models have limited skill predicting precipitation, clouds and radiation; therefore we have developed this coupled model approach with the intention of assimilating NEXRAD-derived precipitation products and GOES-derived radiation products when available (as discussed in Section 3). These products are available at a finer spatial resolution than that of a typical mesoscale model and therefore should provide increased accuracy in the coupled model system.

3.1.3 Communication and I/O

The final key issue in the coupling problem is the efficient communication of information between the host model and the LSP as well as the efficient storage of model outputs on disk. Towards this goal, we have utilized the PVM extensions to the I/O API (Coats, 1998a), which is built on top of the NetCDF (Unidata, 1998) libraries. These extensions are discussed in more detail in Coats et al. (1999), and provide the capability for selective direct access to "virtual" files or "mailboxes" that enable coupling without a scheduler.

3.2 Coupling Modes

Following the concepts of aggregation, disaggregation and communication discussed above, three modes of coupling for TOPLATS and MM5 have been incorporated into the design. First, either model may be configured to accept the other model's output in a 1-way mode, so that previously archived output may be used to "force" or provide the necessary boundary conditions for the other model. For example, as shown in Figure 7, this 1-way coupled mode can be potentially useful for retrospective simulations of air quality exceedance episodes, in which case the latent and sensible heat fluxes from TOPLATS are derived using observed meteorological data and subsequently input into MM5.

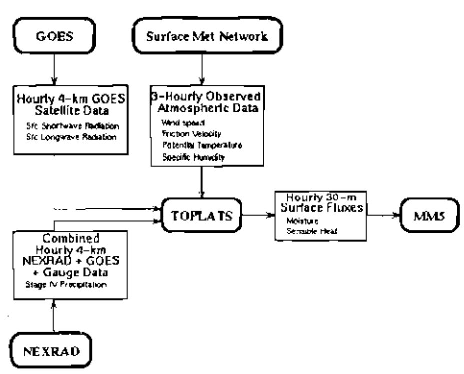


Figure 7. Schematic illustrating 1-way coupling from TOPLATS to MM5. TOPLATS in this case is forced with observed meteorological data

Figure 8 illustrates the typical coupling mode for forecast applications, 2-way coupling, in which the two models operate simultaneously to produce forcing input for one another. Although this coupling mode has the desirable feature of mass and energy conservation, the primary drawback of using MM5 output to provide forcing data for TOPLATS is that meteorological models can only be expected to produce realistic results for short periods in the absence of actual meteorological data. To deal with this potential problem, particularly in the case of radiation and precipitation, which are known contain biases related to unresolved cloud processes in meteorological models, a "1.5-way" coupling mode is illustrated in Figure 9.

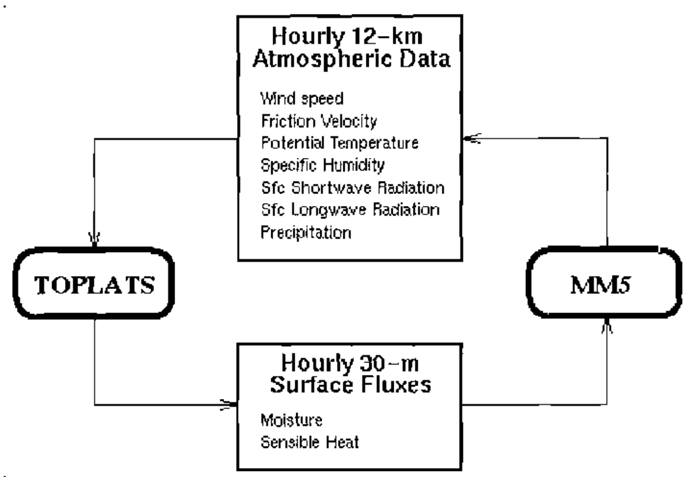


Figure 8. Schematic illustrating 2-way coupling.

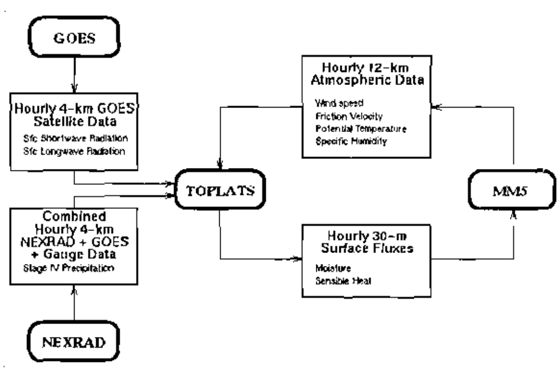


Figure 9. Schematic illustrating 1.5-way coupling. This intermediate coupling mode incorporates remotely-sensed data to reduce known biases in meteorological prediction.

The design of the coupling is flexible in that PVM extensions to the I/O API allow the coupling mode to be specified at run-time. This specification is accomplished via an environment variable TCPL_COUPLING_MODE, which is a bitmap specifying TOPLATS to MM5 coupling, MM5 to TOPLATS coupling, and the use of additional data sources in the coupling. Within TOPLATS, the finest possible MM5 grid is used to derive the necessary forcing data at runtime.

4: Assimilation of remotely sensed data into TOPLATS

The third and fourth (under a no-cost extension) years of the project focused on implementation of remotely sensed sources of data in the TOPLATS model. Forcing data is the time-varying meteorological data that drives a TOPLATS simulation and includes air temperature, relative humidity, wind speed, barometric pressure, precipitation, downward shortwave (solar) radiation, and downward longwave (terrestrial) radiation. Two sources of remotely sensed forcing data implemented in this project for TOPLATS include 1) NEXRAD Stage IV multi-sensor (radar plus rain gauge) data, which provides precipitation coverage for the study domain; and 2) GOES-derived SRB radiation products, which provides downward shortwave (solar) radiation for the modeling domain.

4.1 NEXRAD Precipitation Data

The NEXRAD Stage IV product is a national mosaic of hourly rainfall accumulations on the approximately 4km HRAP grid. These data are available from the GCIP archive (GCIP, 1996), which also contains a detailed description of the data processing procedures and the HRAP grid. We have developed a preprocessing script, called the NEXRAD "filter", which converts these data into a format directly readable by TOPLATS. NEXRAD data is generated from radar coverages of an area, and consist of images of precipitation intensity that cover large areas. NEXRAD data is therefore capable of capturing the high spatial variability exhibited by precipitation that gage or station data often misses. For this reason, NEXRAD is often recommended as the primary source of precipitation data for TOPLATS applications. It is important to note, however, that NEXRAD data does not provide any of the other six forcing parameters required by TOPLATS. Figure 10 shows a NEXRAD image from eastern North Carolina.

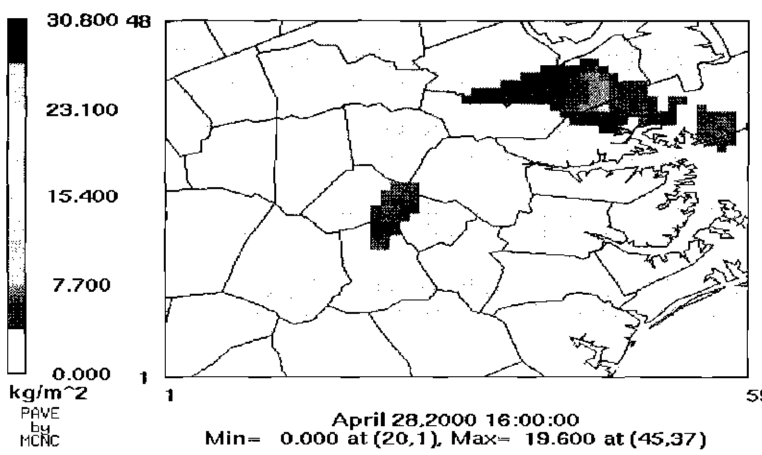


Figure 10: Example NEXRAD Image for Neuse River region, North Carolina.

This figure portrays precipitation intensity for one hour on an approximately 4.7-km grid, and very clearly illustrates the spatial variability of rainfall over a mesoscale area. Gage data may or may not accurately represent such an event, depending on the placements of the gages. Because

NEXRAD data is derived from radar images, which may be influenced by atmospheric conditions, this data is also subject to error and so should be quality checked. Although radar-only sources of NEXRAD data are available, we have chosen to implement the multi-sensor (radar plus rain gage) product in our simulations to reduce the potential biases known to exist in radar-only products. Cumulative volumetric plots of NEXRAD data and gage data from one or more nearby stations can show biases that may be present in the NEXRAD data.

4.1.1 Temporal interpolation

NEXRAD hourly rainfall accumulations are reported as the total rainfall for the hour preceding the reported time, e.g., the accumulation at 11:00 Z represents rainfall from 10:00-11:00 Z. Therefore, for the case that TOPLATS time steps are hourly, and observational data is available on the hour, then the TOPLATS time steps are one-half hour out of phase with NEXRAD data. For this case, NEXRAD data should be imported "half an hour late" so that the phase error is opposite the natural TOPLATS phase error (due to its catchment-wide instantaneous response to rain events and the corresponding "instantaneous" water-transport that this implies. For example, NEXRAD precipitation rate data valid for the 10:00-11:00Z hour should be used for the TOPLATS time step that advances state-variables from 10:30Z to 11:30Z.

In the case that TOPLATS time steps that are much less than one hour, and fit entirely within NEXRAD time steps, then TOPLATS should use the NEXRA data valid for the time step. For example, a TOPLATS time step that advances state-variables from 10:40Z to 10:50Z should use the NEXRAD precipitation rate data valid for the 10:00-11:00Z hour. Other possibilities are forbidden operationally.

4.1.2 Filters

A preprocessor (or "filter") script has been developed to prepare NEXRAD MUL4 (multi-sensor Stage IV) data for input to TOPLATS. The csh loops through a specified date/time period and performs three functions: 1) conversion from GRIB to I/O API/NetCDF format; 2) windowing of the data from the national HRAP grid to a specified project subset; and 3) filling in missing data periods to ensure a continuous record.

4.1.3 Reader-method

The implementation of NEXRAD data within TOPLATS is accomplished via a "reader-method", by which NEXRAD data may be selected as a precipitation input method at run-time as part of a list of reader-methods in the TOPLATS run script. The environment variable list "PPTMS_MTD" should include the reader-method "NEXRAD_PPTMS" in order to read NEXRAD data. If NEXRAD data is missing, the reader-method fails, and TOPLATS reverts to the next reader-method in the PPTMS_MTD list.

4.2 SRB Radiation Data

In addition to NEXRAD precipitation data described in the previous section, TOPLATS may utilize downward solar radiation data products derived from Geostationary Operational Environmental Satellites (GOES) by the GEWEX Continental Scale International Project (GCIP) and GEWEX Americas Prediction Project (GAPP) Surface Radiation Budget (SRB) (Pinker and

Lazslo, 1992; Pinker et al, 2001) project. Surface Radiation Budget (SRB) data has the following potential set of variables, according to http://metosrv2.umd.edu/~srb/gcip/cgi-bin/historic.cgi, with one variable and time period per file.

- Surface downward flux (a.k.a. GSW (in MM5) or RSD (in TOPLATS))
- Surface downward photosynthetically active radiation (PAR)
- Top of atmosphere downward flux
- Top of atmosphere upward flux
- Cloud cover fraction
- Surface Skin Temperature; and
- Surface albedo

The following file types are generally available: instantaneous, hourly and daily.
The instantaneous values at the instant of observation are not properly time-stepped, and would require further processing to generate time-stepped output to be usable by TOPLATS. Daily average data are not expected to be useful for most modeling applications, although they might be useful for analysis. The hourly average data are most appropriate for production applications, and can be appropriately time stamped on the half-hour so that time-interpolation without phase error is possible.

Note also that there are at least two different grids in this dataset, the pre-July 2001 51×111 grid with lower left corner (in I/O API terms; see http://envpro.ncsc.org/products/ioapi/) at (XORIG,YORIG) = (-125.25,24.75) and the post-July 2001 grid with lower left corner at (XORIG,YORIG) = (-126.25,23.75). GRIDDESC grids LL_SRB05_V1 and LL_SRB05_V2 will be the names of the respective pre-July 2001 and post-July 2001 grids.

4.2.1 Temporal interpolation

In the "hour-average" data files, the "instantaneous" satellite scan RSD has been re-normalized by the hour-mean MUBAR of the cosine of the solar zenith angle, to get what they label "hourly averaged" RSD. Additionally, there is a minor problem that the data is "on the half hour" unlike most other observational meteorology, which is "on the hour". One wishes to reconcile the two types of input data time step sequences without losing resolution in either. It turns out that the supplier did not do the "correct" normalization when going from the "instantaneous" to the "hour-average" solar fluxes: they renormalized "instantaneous" fluxes by the factor

mu(T) / MEAN(from t=H to t=H+1(mu(t)))

where mu(t) is the cosine of the solar zenith angle at time t. Then they replaced all negative values by a "missing"-flag value of -999.0. When this is done, there will be cancellations in the computation of that mean for hours when mu takes on both positive and negative values (i.e., during hours that contain a sunrise or sunset) and therefore unrecoverable underestimates of RSD for sunrise/sunset hours. They should instead have renormalized by the factor

mu(T) / MEAN(from t=H to t=H+1 (MAX(mu(t), 0.0))

We developed the following algorithm to deal this problem as well as with the problem of missing and/or defective records in the input data (as determined by manual QA examination). We also developed program GSW2SOLAR that implements the input-part of this algorithm.

4.2.2 Filters

There are two filters (or preprocessors) that have been developed to handle SRB data. Both are written as Fortran-90 programs, with the usual control by environment-variable string-lists. The first filter, SRB2IOAPI, reads potentially multiple SRB files for a common grid and time period, and merges them into an I/O API GRIDDED file SRB_CRO_2D over that time period. Potential variables and time step sequence-types for this file are as given above. Note that all of these files should be PAVEable, etc., for analysis and QA purposes. It is essential that the output of this filter undergo manual QA at this point. For example, manual QA checking of the August 25-31, 1998 SRB data with PAVE shows that there are several missing daytime hours, as well as one hour that has clearly erroneous satellite-scan values. This step is used to identify "missing" or "unacceptable" values to be removed in the second SRB filter program described below.

The second filter, GSW2SOLAR, reads the entire SRB_CRO_2D SRB/MUBAR data set produced by the SRB2IOAPI filter above and then zeros out SRB for a user-selected set of time steps that fail the manual QA step above. Further, GSW2SOLAR zeros out sunrise/sunset hours, where the existing renormalization is incorrect as described in the time interpolation discussion above.

At each valid column, row, and hour, GSW2SOLAR calculates the variable SOLAR(c,r,h) = SRB(c,r,h)/MUBAR(c,r,h) that represents the solar radiation incident on a zenith-normal plane; SOLAR(c,r,h) is initialized to zero elsewhere. For each row and column in the grid, GSW2SOLAR fills in the "holes" in SOLAR by time-interpolation from valid values in the interior of the time period, and by extension-by-constant for the initial and terminal segments (e.g., If h is the first hour for which SOLAR(c,r,h) > 0, we set all values from SOLAR(c,r,1) to SOLAR(c,r,h-1) = SOLAR(c,r,h).)

Finally, GSW2SOLAR writes variable SOLAR out to file SOLAR_CRO_2D, which is the final form used by the SRB readers, to be described in the next section. For this file, variable SOLAR is defined everywhere, and time interpolation is handled properly following the discussion above.

4.2.3 Reader-Method

The implementation of SRB data within TOPLATS is accomplished in a manner similar to the NEXRAD data: the SRB data may be selected as an input method at run-time as part of a list of reader-methods in the TOPLATS run script. The environment variable list "RSD_MTD" should include the reader-method "SRB" in order to read SRB data.

The SRB reader-method does time-interpolation of SOLAR to the center of the current time step, calls a subroutine MUFACTOR, described below, to compute the correct time step mean solar zenith angle cosine factor MUFAC, and multiplies the two, to arrive at a current time step mean value for the SRB-grid gridded GSW. Note that since MUFACTOR correctly deals with sun-over-the-horizon effects, we actually manage to resolve sunrise and sunset correctly even with very short TOPLATS time steps. TOPLATS reader-method SRB then does bilinear spatial interpolation of the resulting GSW to the superpixel centroids in a manner similar to other reader-methods. Subroutine MUFACTOR calculates the gridded value of

MUFAC(c,r,T,DT) = MEAN(t=T t=T+DT (MAX(mu(t), 0.0)))

which has the property that SOLAR(c,r,T+DT/2)*MUFAC(c,r,T,DT) is the correctly normalized mean value of GSW for the time step from T to T+DT, where SOLAR(c,r,T+DT/2) is the time-interpolated value at the center of that time step.

Figure 11 shows an example SRB image from the Houston/Galveston region of Texas. Like station and NEXRAD data, SRB data must be formatted for input to TOPLATS with a two-step preprocessor called the "SRB filters". The two-step process involves converting the raw data from the SRB archive to I/O API format to support manual quality control.

Layer 1 RSDc

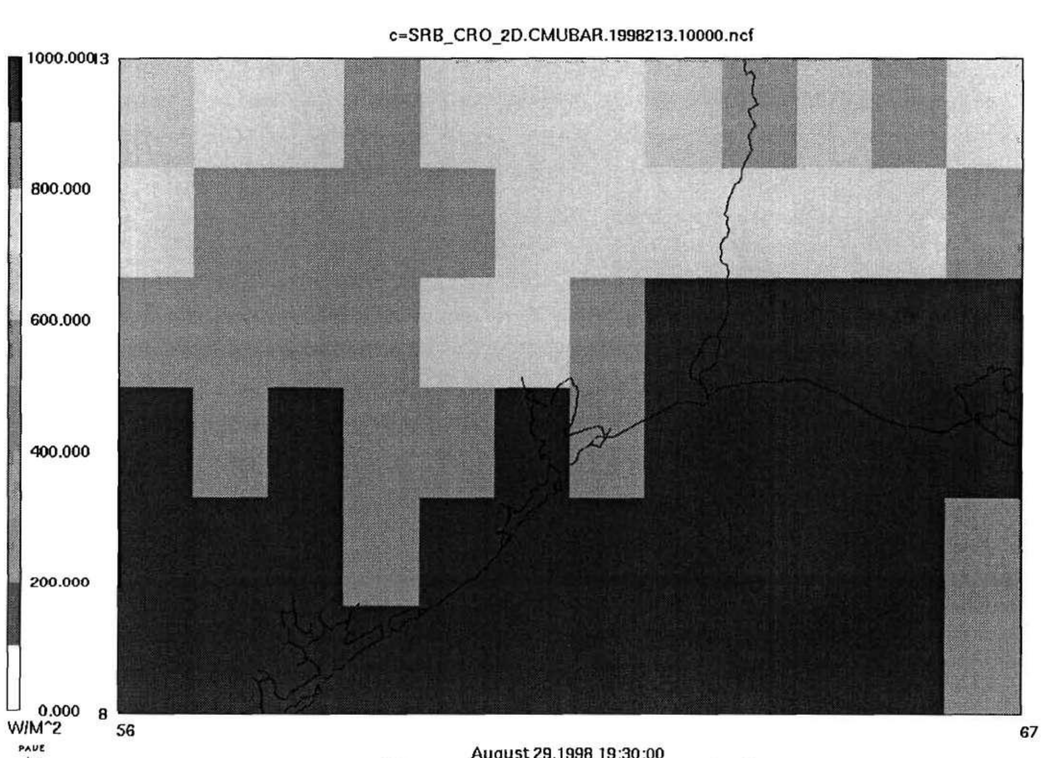


Figure 11. Example SRB Downward Solar Radiation (RSD) image for Houston/Galveston, Texas region.

5: 1-D TOPLATS/MM5 Coupling

As discussed in Section 2, the initial application of the Sparse-TOPLATS model was the Washita '94 field experiment. In addition to the extensive surface meteorological, surface flux, and soil moisture datasets, three-hourly atmospheric sounding data was collected throughout the period from August 18-23, 1994. This period was characterized by a mesoscale precipitation event on August 17-18, followed by a drydown, except for some brief showers on August 20. For the purposes of the 1-D simulations, August 18 is considered a "wet" day, and August 23 is considered a "dry" day. The 1-D coupled results are summarized in an AMS preprint (McHenry et al., 1999), and are the subject of a manuscript in preparation (Peters-Lidard et al., 2002). Below we discuss the model configuration and results for "wet" and "dry" days, and the entire episode.

5.1 Model Configuration

The coupled model consists of two component models:

1. The Sparse-TOPLATS model discussed in the previous sections; and
2. A 1-D column version of the non-hydrostatic PSU/NCAR MM5 (Grell et al., 1994).

The coupling is designed for expansion to 3-D, as will be discussed in the next section. TOPLATS is driven by input downward solar radiation and precipitation at the canopy top, along with atmospheric state variables such as temperature, mixing ratio, and wind speed. TOPLATS accounts for lateral heterogeneity in topography, soils, and vegetation by solving independent and explicitly distributed water and energy balances for each computational element in a GIS framework. It is typically applied at horizontal resolutions of 30-100 meters.

The MM5-1D is configured with a 1.5 order TKE boundary layer scheme (Gayno, 1994), a deep convection scheme (Kain and Fritsch, 1993), an explicit moisture scheme, and an atmospheric radiation scheme (Dudhia, 1989). A shallow convection scheme is being developed under another project and will be added in due course. The vertical sigma coordinate was divided into 32 layers, with 18 layers confined to the lower 2000 meters of the atmosphere and a half-layer height of about 10m in the surface layer.

From August 18-23, 1994 an Intensive Observation Period (IOP) of the NASA/USDA field experiment Washita '94 was conducted in the nearly 600 square km Little Washita Watershed (LWW) in southwest Oklahoma. The experimental goal was the investigation of land-atmosphere interactions and remote-sensing of soil moisture and temperature. During Washita '94, 3-hourly atmospheric radiosounding data was collected from 6AM local time until 6PM local time. In addition, half-hourly surface measurements of latent and sensible heat flux, as well as standard surface meteorological variables were collected (Starks and Humes, 1996).

Within that period, the weather on August 23 was particularly favorable for applying a 1-D atmospheric model—a summer cold front had passed about 36 hours earlier, and a large Pacific high pressure system was slowly progressing across the Great Plains. Skies were mostly clear all day, and both surface and 500mb winds were light. Slowly varying geostrophic forcing was in place as the axis of the surface high pressure moved eastward and a 588dm upper level ridge built across the region from the southwest.

To test the model coupling, a typical 12-km MM5 grid box was geo-located within the LWW domain covered by TOPLATS, as shown in Figure 12. Though not absolutely necessary for the 1-D experiment, the geo-location was conducted in order to prepare for 3-D test simulations.

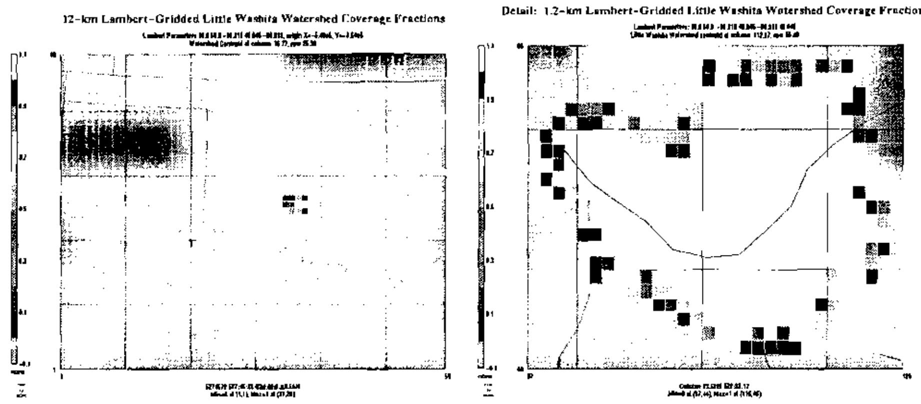


Figure 12 a (left) and b (right), showing the location of the geo-located MM5 grid on the TOPLATS Little Washita domain.

In Figure 12a, the white grid lines are the 12-km MM5 cells, and in Figure 12b, they are black. The outline of the Little Washita Watershed (LWW) is shown in Figure 12b as fractional coverages of the 30-meter TOPLATS grid on the 1km white gridlines. The Little Washita River is evident near the center of the catchment.

TOPLATS was run at 30-meter resolution and an hourly timestep for the duration of the period by forcing it with observations: 1.5m air temperature, humidity, and downward solar radiation from the Agricultural Research Service (ARS) Micronet stations within the LWW, and 2m wind speed, and pressure from the nearby Oklahoma Mesonet. In addition, NEXRAD stage II hourly precipitation estimates from the Twin Lakes, OK radar on a 4-km grid were used as rainfall inputs.

TOPLATS was initialized on August 18th by setting the surface soil moisture to field capacity, and by setting the initial water table depth to yield observed baseflow. Rainfall on the 18th reduced the sensitivity to these initial conditions. Transmission zone soil moisture was set to give a hydrostatic pressure profile between the surface and the water table depth, and initial skin and soil temperatures were set to observations. TOPLATS performed reasonably well against the measured surface-energy budget for the entire period.

In the present example, the coupled model was run without any feedback from MM5-1D to TOPLATS—i.e., 1-way coupling as discussed in Section 3. In this paradigm, TOPLATS is driven entirely by the observations and then passes calculated skin temperature and fluxes of sensible and latent heat to the TKE-PBL scheme within MM5-1D.

Because the hydrological spatial scales—on the order of 30-100m—are highly sub-grid with respect to meteorological meso-scales, aggregation of PBL forcing quantities from TOPLATS must be accomplished as part of the coupling. We used area-weighted linear averaging for the fluxes and skin temperature, and are investigating the incorporation of additional perturbation quantities into the TKE-scheme on the basis of the available sub-grid TOPLATS information.

To drive the atmospheric column, the upper air observations provided by the NSSL/Mobile CLASS collection system at 11UTC on each day of the experiment was used to determine initial vertical temperature, moisture, and wind profiles. A smoothly varying geostrophic wind-profile was also estimated from the 3-hourly observations collected at 14UTC, 17UTC, 20UTC, and 23UTC on the same day, following a single-site estimation technique.

Daytime (11UTC to 23UTC) simulations were conducted using MM5-1D in both coupled and uncoupled form. The uncoupled simulation—performed as a control—used the standard MM5 land-surface "slab" force-restore method (Grell et al., 1993). This includes land-surface parameters (albedo, soil moisture availability, thermal conductivity, emissivity, and roughness length) from the MM5 dominant land-use type, agriculture, for the geo-located cell. It also used a substrate temperature based on the average of 12UTC and 00UTC TOPLATS-predicted skin temperatures.

The coupled simulation used an average TOPLATS derived soil moisture availability for each day of the simulation (needed for computing skin virtual potential temperature in the TKE-PBL scheme), and an effective roughness length calculated from the values corresponding to land-cover types in the LWW. All other land-surface parameters were represented within TOPLATS for the coupled simulation. Common to both simulations was the initial 11UTC average TOPLATS LWW skin temperature.

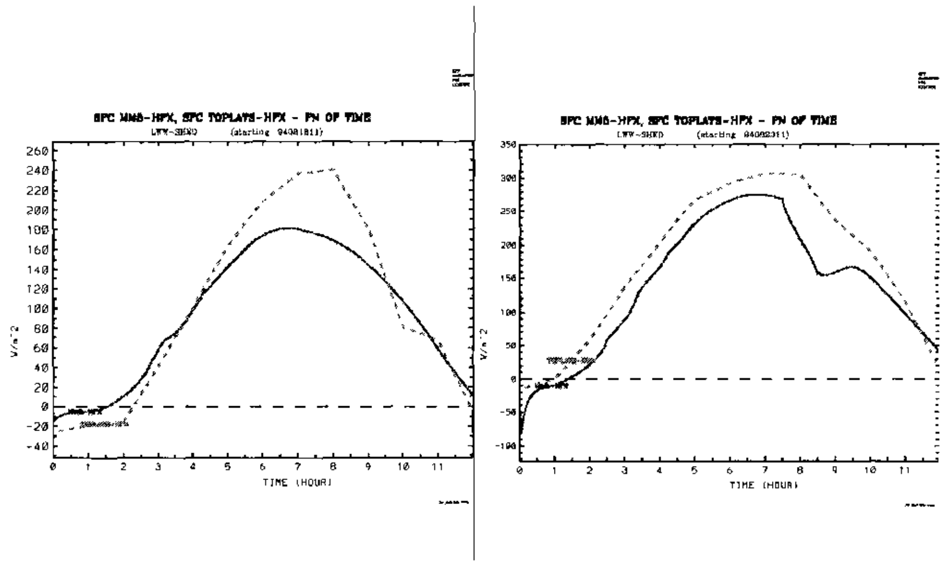
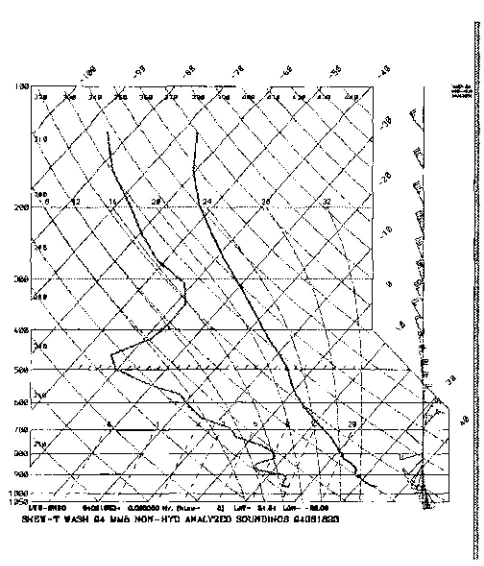


Figure 13. MM5-TOPLATS (dashed) and MM5-SLAB (solid) sensible heat flux time series for "wet" (Figure 13a: August 18) and "dry" (Figure 13b: August 23) days of the Washita '94 IOP.

5.2 "Wet" Day Results: August 18, 1994

Figure 13a illustrates the MM5-SLAB and MM5-TOPLATS sensible heat fluxes for August 18, 1994. The resulting differences in atmospheric structure due to these differences are shown in Figure 14a-c, which illustrates the observed, MM5-SLAB and MM5-TOPLATS 23UTC (5PM Local Daylight Time) thermodynamic profiles on skew-T diagrams.



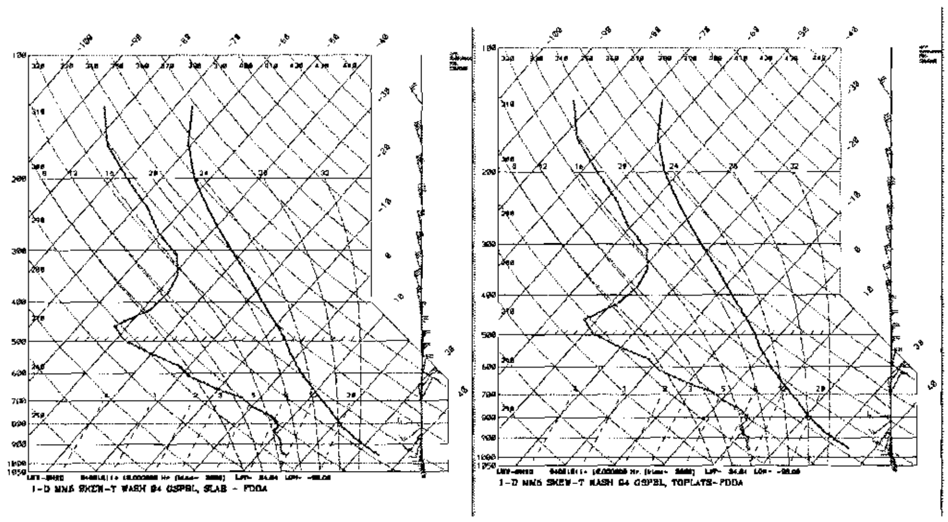


Figure 14. Observed (top), MM5-SLAB (lower left), and MM5-TOPLATS (lower right) simulations of the August 18, 1994 "wet" day.

From the surface to the bottom of the free atmosphere, there are three distinct layers. Layer 1 is a superadiabatic (SA) layer persisting below about 950mb, corresponding with a surface layer slightly moister than that just above the SA layer. Above this convective surface layer, layer 2 extends from about 950mb to 900mb, where the atmosphere is very well-mixed. Layer 2 features a dry adiabatic lapse rate and a nearly uniform water vapor mixing ratio of about 11 g/kg. Layer 3, between 910mb and 860mb, appears to be partially mixed, with a slightly stable lapse rate and a sharply declining mixing ratio going from 11 g/kg to about 6.5 g/kg at 860mb. Above 860mb the transition to the free atmosphere is complete. Within the free atmosphere the structure is very stable and relatively dry, except for a moist layer centered at 800mb.

For both simulations, an Ekman-layer balance of forces was used to compute wind-speed and direction in the PBL. This captured the wind magnitude well, but underestimates the backing of the wind in the surface layer. The layer 2 temperature profiles are generally too warm in both simulations (by about 2K), and therefore, the surface layer stability is not well-represented in either model. The layer 2 humidity profile in the MM5-SLAB simulation is generally closer in magnitude than the MM5-TOPLATS profile, but is not well-mixed. The MM5-TOPLATS profile is well-mixed in accordance with the observations, which suggests that the TKE and flux profiles may be better represented in the MM5-TOPLATS simulations. This mixing is likely due to the larger magnitude of the sensible heat flux, as shown in Figure 13 a. Neither model does a credible job of simulating the drying in layer 3, although MM5-TOPLATS is clearly superior to MM5-SLAB. Within the free atmosphere, the structure is dry and stable but somewhat moisture than observed. Above about 800mb, the thermodynamic structure of the MM5-TOPLATS model is indistinguishable from the MM5-SLAB model, an indication of the lack of advective processes in the model.

Figure 15 illustrates the modeled and observed PBL heights for August 18. It is clear that both simulations perform rather poorly, presumably due to an absence of large-scale forcing, such as subsidence and large-scale advection. This suggests that certain situations may require a full 3-D representation in the coupled system.

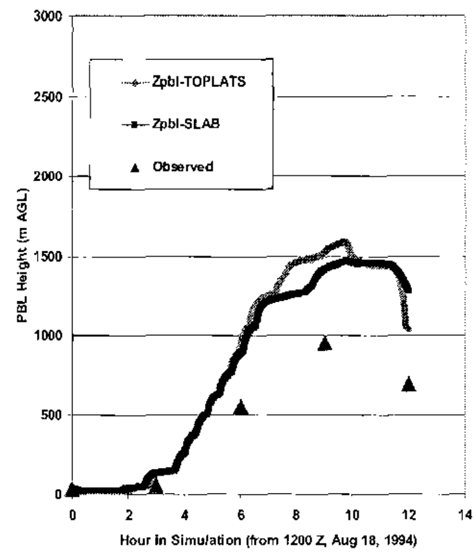
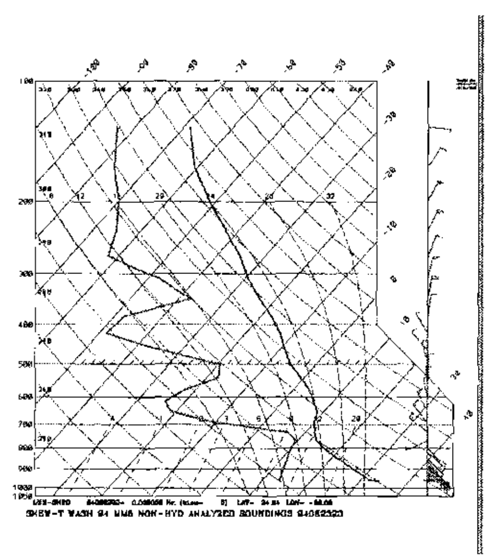


Figure 15. MM5-predicted PBL heights for "wet" day (August 18, 1994). It is likely that failure to account for large-scale subsidence in the 1-D model led to mediocre performance for both models.

5.2 "Dry" Day Results: August 23, 1994

Figure 13b illustrates the MM5-SLAB and MM5-TOPLATS sensible heat fluxes for August 23, 1994. The resulting differences in atmospheric structure due to these differences are shown in Figure 16a-c, which illustrates the observed, MM5-SLAB and MM5-TOPLATS 23UTC (5PM Local Daylight Time) thermodynamic profiles on skew-T diagrams.



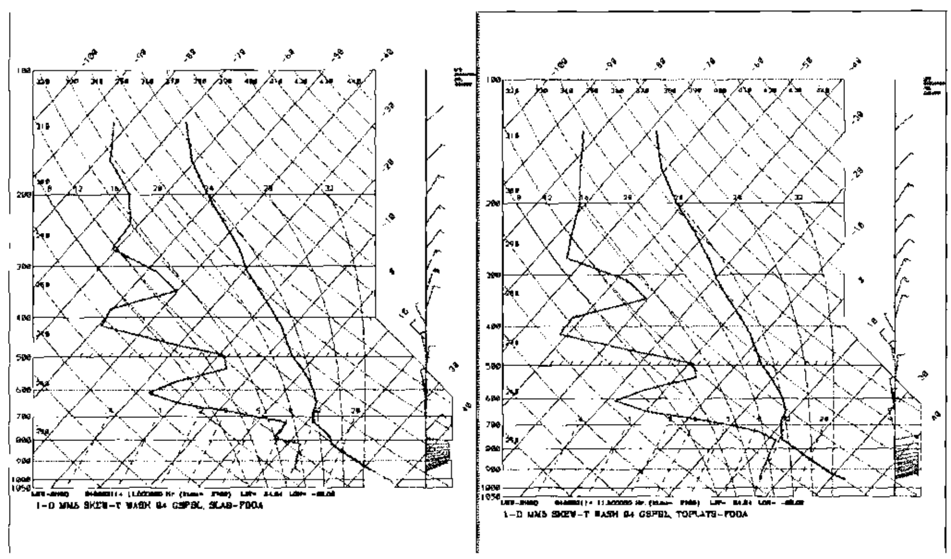


Figure 16. Same as Figure 14, but for the August 23, 1994 "dry" day.

As with August 18, there are there are at least three distinct layers. Layer 1 is a superadiabatic (SA) layer persisting below about 950mb, corresponding with a surface layer slightly moister than that just above the SA layer. Above this convective surface layer, layer 2 extends from about 950mb to 830mb, where the atmosphere is very well-mixed. Layer 2 features a dry adiabatic lapse rate and a nearly uniform water vapor mixing ratio of 9.3 g/kg. Layer 3, between 830mb and 730mb, appears to be partially mixed, with a slightly stable lapse rate and a sharply declining mixing ratio going from 9.3 g/kg to about 5.5 g/kg at 730mb. Above 730mb the transition to the free atmosphere is complete. Within the free atmosphere the structure is stable and dry.

The most striking feature of the modeled atmospheric profiles occurs in the MM5-SLAB simulation shown on the left in Figure 16. At approximately 810mb, a sharp decrease in humidity is seen, and further analysis of the model results reveals that a deep convective cloud was erroneously initiated at approximately 2000 UTC. The MM5-TOPLATS simulation shown on the right of Figure 16 does not illustrate this behavior. Below about 810mb, both models perform similarly, and both are generally too wet and too warm relative to the observations.

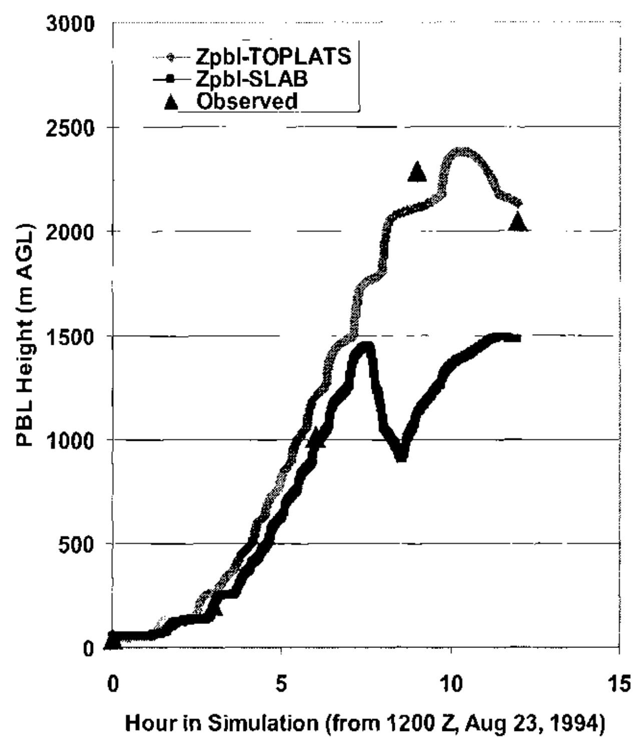


Figure 17. MM5-predicted PBL heights for "dry" day (August 23, 1994). In this case, the TOPLATS-MM5 model performance is clearly superior to that of the SLAB-MM5 model, due to the erroneous initiation of a deep convective cloud.

Figure 17 clearly illustrates the impact of the erroneous deep convection on the PBL heights, which are diagnosed as a function of a TKE threshold. This cloud then interacts in MM5 with the radiation budget, which reduces the sensible heat flux and therefore the PBL height. The radiosonde observations indicate excellent agreement with the TOPLATS-MM5 model.

5.4 Episode Summary

The 1-D MM5 model was run for each day of the Washita '94 IOP to examine the time-behavior of modeled versus measured atmospheric profiles. Table 1 gives a summary of temperature and dew point temperature errors for the entire atmospheric column for each day of the run, as well as for all six days of the episode. The results indicate that the TOPLATS errors in both quantities are generally lower than those from SLAB, although the improvement in dew point temperature is on the order of 0.5 K versus 0.1 K for temperature.

Table 1. Episode temperature (T) and dew point temperature (Td) error statistics (K) for the 1-d coupled runs. Values represent vertical column averages for the entire model domain.

	6-day average	8/18/1994	8/19/1994	8/20/1994	8/21/1994	8/22/1994	8/23/1994

SLAB	T error	0.52	0.53	0.56	0.75	0.30	0.47	0.61
	Td error	2.02	1.66	1.22	1.95	1.93	1.33	4.47
TOPLATS	T error	0.43	0.58	0.30	0.41	0.41	0.50	0.39
	Td error	1.56	1.64	1.18	1.25	1.71	1.35	2.27

Table 2 is similar to Table 1, except that the error statistics are for the first ten sigma levels rather than the entire column, to get a better estimate of the boundary layer behavior. As discussed previously, the atmospheric column above the boundary layer was "nudged" to the observed profile to represent non-local influences not able to be represented with a column model. The temperature errors in Table 2 are generally higher than those in Table 1, although the dew point temperature errors are higher. As with the total column results, the TOPLATS-MM5 simulations are generally superior to the SLAB-MM5 runs, with temperature differences of approximately 0.3 K and dew point differences of approximately 0.1K.

Table 2. Same as Table 1, but for the first 10 sigma levels, which are a surrogate for the atmospheric boundary-layer.

		6-day average	8/18/1994	8/19/1994	8/20/1994	8/21/1994	8/22/1994	8/23/1994
SLAB	T error	1.04	1.10	1.46	1.37	0.42	1.05	0.93
	Td error	1.19	0.47	0.86	0.92	1.58	0.97	2.53
TOPLATS	T error	0.77	1.01	0.38	0.72	0.84	0.87	0.74
	Td error	1.07	0.94	0.77	0.97	0.95	1.03	1.88

6: 3-D TOPLATS/MM5 Coupling

In order to effectively test the 3-D TOPLATS/MM5 coupled model, a mesoscale modeling domain with adequate validation data was required. This requirement, along with the availability of other funding from the Texas Natural Resource Conservation Commission (originally from EPA), led us to choose the August 25-31, 1998 ozone-exceedance episode in the 8-county Houston-Galveston Non-Attainment Area as our 3-D application. As part of this work, we developed and applied a Sea-Surface Atmosphere Transfer Scheme (SSATS), which is driven with observed Sea Surface Temperature (SST) data from a combination of in situ (NOAA PORTS) and remotely sensed (CoastWatch AVHRR) sources. This model is fully documented at http://www.emc.mcnc.org/projects/TNRCC-projects/tnrcc_public.html, and will not be described here. The 3-D coupled results will be described at the upcoming MM5/WRF workshop (Peters-Lidard et al., 2002). Below we discuss the model configuration and results for the episode.

6.1 The Houston-Galveston 3-D Application

6.1.1 TOPLATS Configuration

The TOPLATS Study Domain (TSD) for this project was set by mosaicking 8-Digit Hydrologic Unit Code watersheds provided by the National Hydrography Dataset (NHD) (USGS, 2001). This domain was chosen to include all watersheds that contain areas of Harris County (Houston), Texas as well as all counties that border Harris. Using this one-county buffer region as a guideline, the domain to model for TOPLATS was set as a large portion of the Eastern Coastal Plains of Texas with an area of approximately 96,000 square kilometers. The region covers an expanse from Matagorda Bay in the most southern point (28.07 N) to near Waco, Texas in the north (31.81 N), and from Lake Charles, Louisiana in the east (93.01 W) to the suburbs of Austin, Texas at the westernmost location (97.37 W)(Figure 18).

The region chosen for this project is much larger than those typically used in previous TOPLATS studies, and is only possible due to the parallel techniques and high performance I/O that have been implemented as part of this research. The TOPMODEL concept assumes that base flow is the same throughout the watershed of interest, and when the watershed is much larger than 500 square kilometers in area, this assumption may be invalid (Sivapalan, 1987). Therefore for a large region such as the HGA study requires, the domain is subdivided into smaller watersheds suitable for TOPLATS. In total the region has been divided into 173 watersheds (Figure 18), each of which has watershed-specific parameters required for TOPLATS.

Parameters for TOPLATS were estimated using readily available Digital Elevation Model (DEM), landcover and soils databases (Figure 19). TOPLATS was then "spun-up" for the period January 1-August 24, prior to coupling, using observed forcing data, including NEXRAD WSR88D precipitation, observed solar radiation, and observed surface-station meteorology including wind-speed, temperature, relative humidity, etc. More details about the TOPLATS databases and spin-up are available online at:
http://www.emc.mcnc.org/projects/TNRCC-projects/ATAQM/ataqmII_report1.pdf

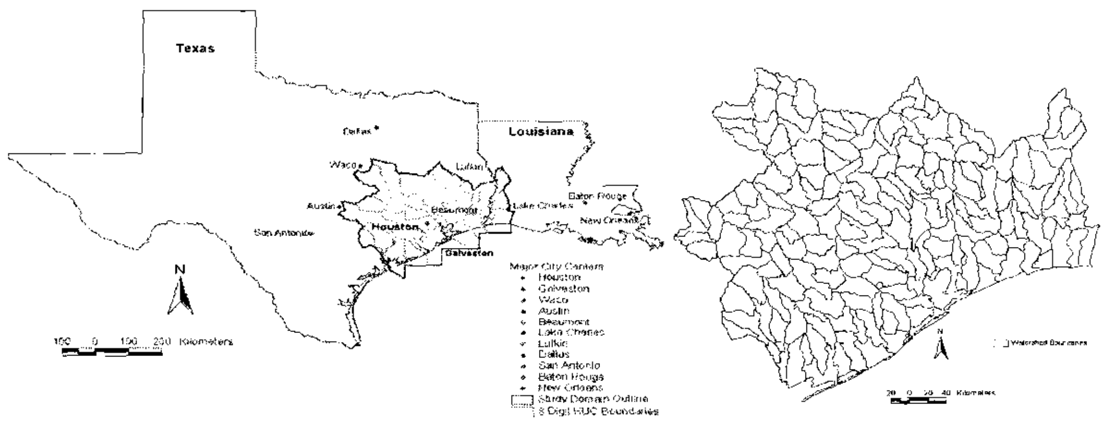
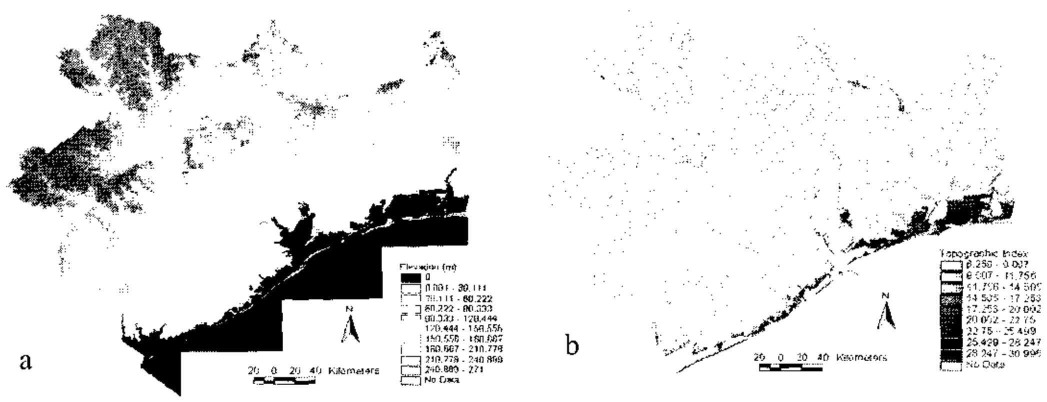


Figure 18. Houston-Galveston study region (left) and delineated watershed boundaries (right).



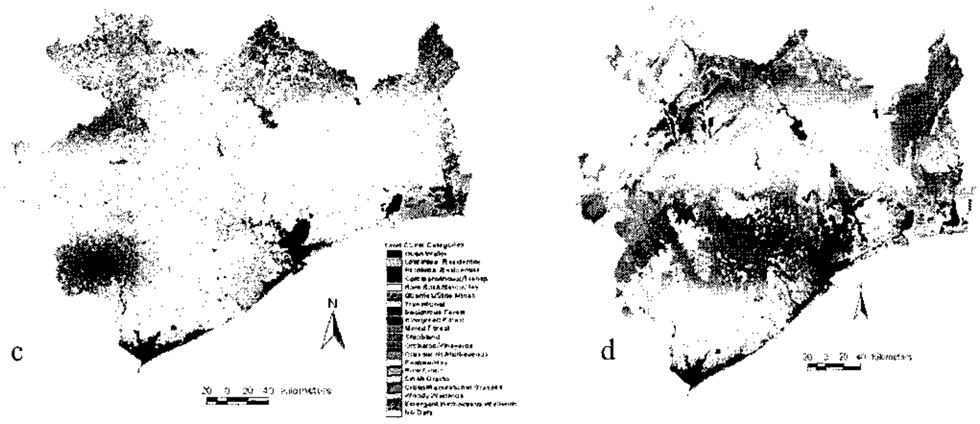


Figure 19. Geographic databases for TOPLATS. Elevation (a), topographic index (b), land cover (c) and soil texture (d).

6.1.2 MM5 Configuration

MM5 was configured using a 36-12-4km nested model with 43 half-sigma layers in the vertical. The MM5 domains are shown in Figure 21.

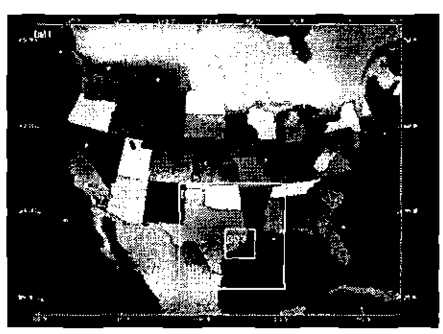


Figure 20. 36, 12 and 4 kilometer MM5 modeling domains.

The physics options chosen for this initial implementation were as follows:

- PBL: Blackadar-VMM (MCNC)
- CONVECTION: KF (36/12 only)
- MOISTURE: Reisner Mixed-Phase (4 only)
- RADIATION: Cloud (lwrad/swrad)

A large number of meteorological modeling data types were considered for use in the project, and many of them were utilized for developing MM5 initial, boundary, and FDDA fields; for driving TOPLATS; or for case analysis. A particular dataset issue relevant to MM5 was the lack of availability of ETA analysis fields for the first part of the episode, August 25-28, 1998. Therefore, the episode was run as two segments.

The first segment was run from August 25, 00Z through August 28, 12Z, (1998) and was based on GDAS initial fields. Since the initial fields were available only at 12-hourly intervals, we ran the 36-km/12-km grids (2-way nesting) twice. The first pass used analysis nudging at 12-hourly intervals. These results were then fed into INTERPB to produce 3-hourly REGRID style fields. These fields were fed back through RAWINS and INTERPF, and the results were used to nudge MM5 with 3-hourly analysis fields. The second segment was less complicated. We used ETA analysis fields (these fields were missing for the first part of the episode, thus leading to the procedures described above) for the second segment, which went from August 28, 12Z through 00Z August 31, 1998. These 3-hourly fields were fed into REGRID, then RAWINS, INTERPF, and finally MM5. For all these runs the 36/12-km grids were run in 2-way nested mode, while the 4-km grid was either a one-way or two-way nest.

6.2 Evaluation

Extensive evaluation against screen-level observations and GOES cloud imagery indicates that the 3-D coupled TOPLATS/MM5 (aka "coupled" or "c2") modeling system performance is superior to that obtained from the original MM5 modeling system using the SLAB (5-layer Dudhia, aka "vanilla" or "van") land surface model. For example, the diurnal 2-m temperature cycle and error statistics for the episode are shown in Figure 21.

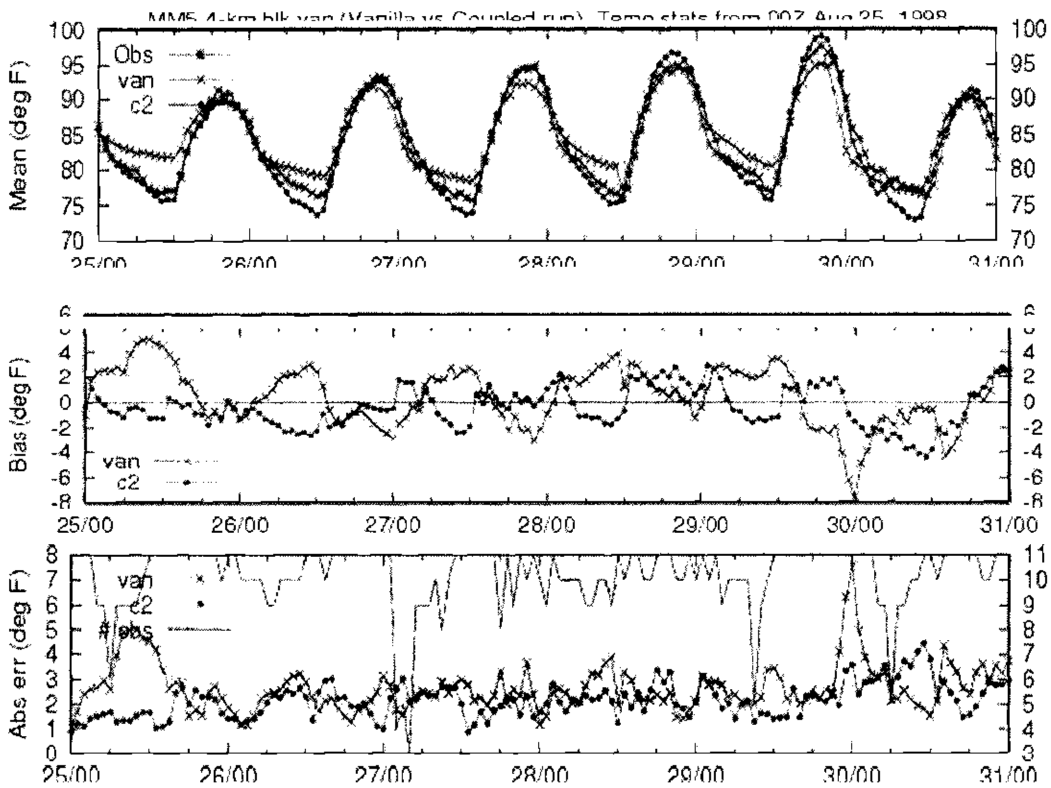


Figure 21. Average 2-m temperature observed at in-situ meteorological stations and modeled with MM5/SLAB ("Vanilla" or "van") and MM5/TOPLATS ("Coupled" or "c2").

Although the diurnal 2-m temperature cycle is clearly improved relative to the original modeling system, the 2-m humidity and 2-m wind results are strongly sensitive to lower limits imposed on wind speed and friction velocity within the HIRPBL scheme, and have a diurnal cycle. To further explore this sensitivity, a number of experiments were set up to examine the impacts of coupling, grid boundary conditions, and the lower limits to wind speed and friction velocity. The naming conventions for these experiments is as follows:

Names of the runs with the lower limits are blk.${ext3612}.${ext4}, and the runs without lower limits are blk.wspd.${ext3612}.${ext4}; where ${ext3612} will be any one of the following three:

1) ${ext3612} = van ==> original vanilla run, using FDDA on both grids with one-way coupling between the two grids. Used as CONTROL or "Vanilla".
2) ${ext3612} = kf5 ==> original setup but with modified KF downdraft to detrain over 50mb deep layer
3) ${ext3612} = kf5.2w ==> change to 2way nest (IFEED =3) with FDDA on the 36km grid only using modified KF downdraft
4) ${ext3612} = kf5.2w.c2 ==> same approach as kf5.2w; but TOPLATS/SSATS-couples on the 12km grid only (not 36). Uses a refined flux-kernel re-computation approach; i.e

calculate the "internal" kernel and use it for MITERING. Uses TOPLATS "MAVAIL" to estimate the QFLX kernel, necessitating a (1,0) trap on MAVAIL

and ${ext4} has the following meaning:

a) ${ext4} = van ==> original vanilla run, using no FDDA.
b) ${ext4} = c2 ==> 1-way coupling to 4km MM5 using c2 flux kernel calculation approach

For example, Figure 22 illustrates the episode average daytime bias in humidity for nine cases, which should be contrasted with Figure 23, which shows the nighttime humidity bias. In Figure 22, the best performance is for the no-lower limit coupled case, with a general trend of improvement in the coupled model relative to the original or "vanilla" model. However, Figure 23 shows that this trend is exactly the opposite at nighttime, with increasing bias in the coupled model, and degradation of results when the wind speed lower limits are removed. Therefore, it is likely that the coupling of TOPLATS is offsetting compensating errors in the original model.

Figure 24 helps explain the differences in performance in the mixing ratio. Shown in Figure 24 is the nighttime average bias in the V (east-west) component of the wind. As shown, the highest magnitude V-component bias occurs for the same cases for which the highest magnitude nighttime mixing ratio bias occurs, which suggests that the bias may be related to the inability to represent the sea-breeze/land-breeze at nighttime.

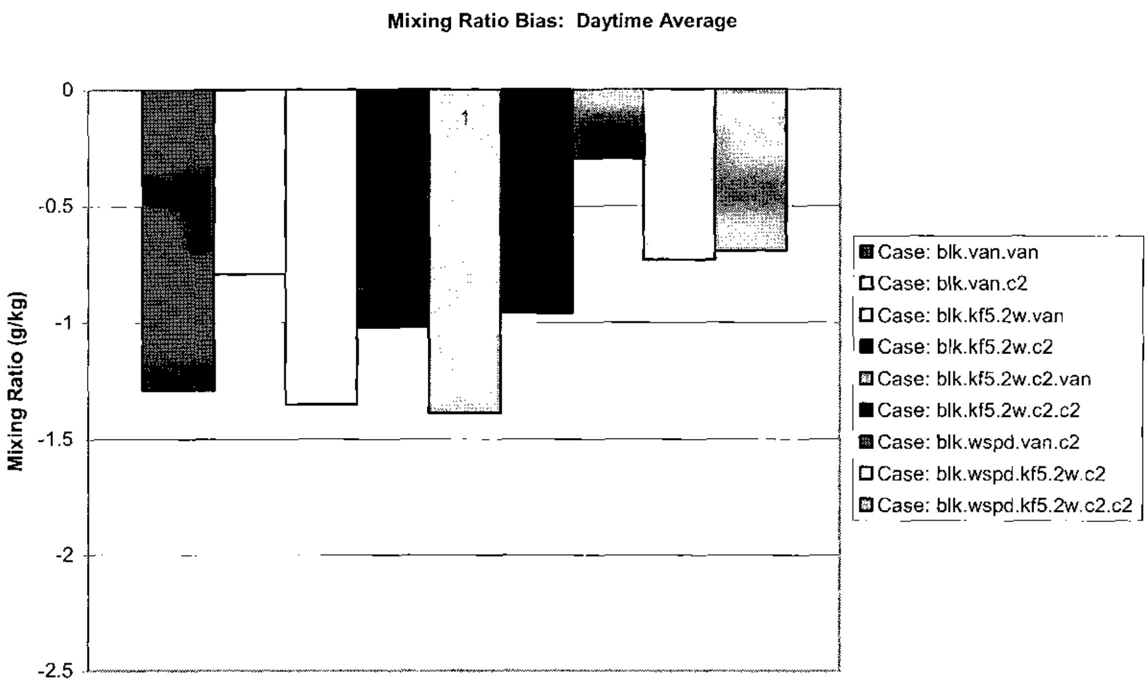


Figure 22. Daytime average bias in mixing ratio (q) for the nine cases described in the text.

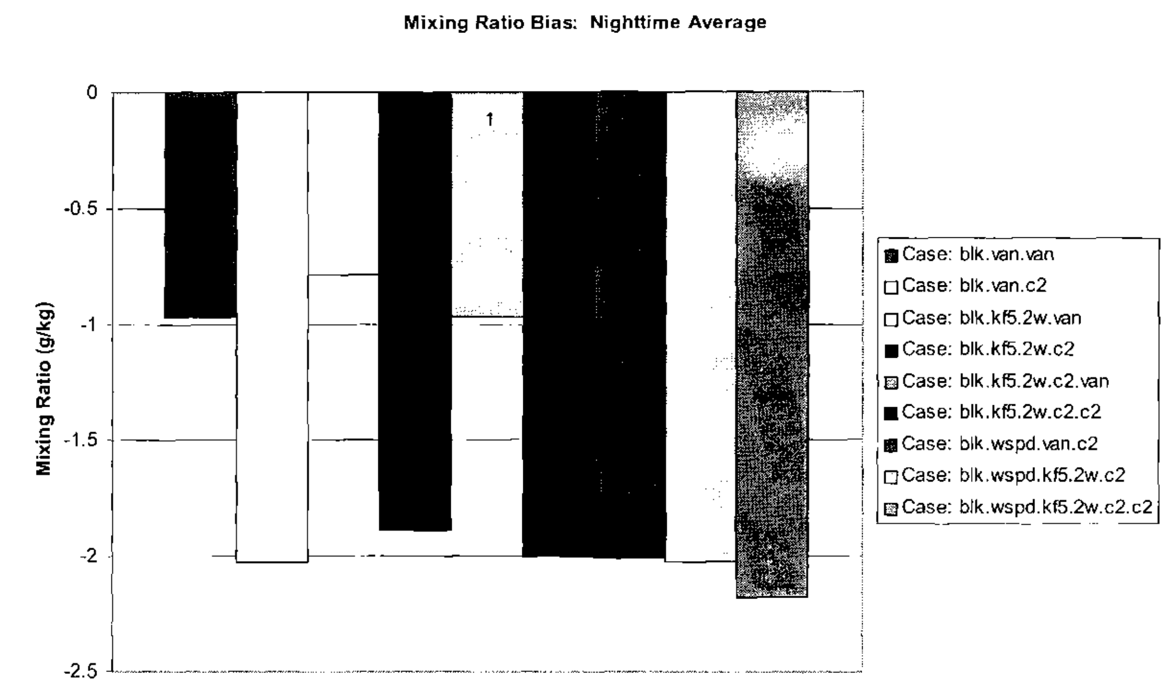


Figure 23. Same as Figure 22, but for nighttime.

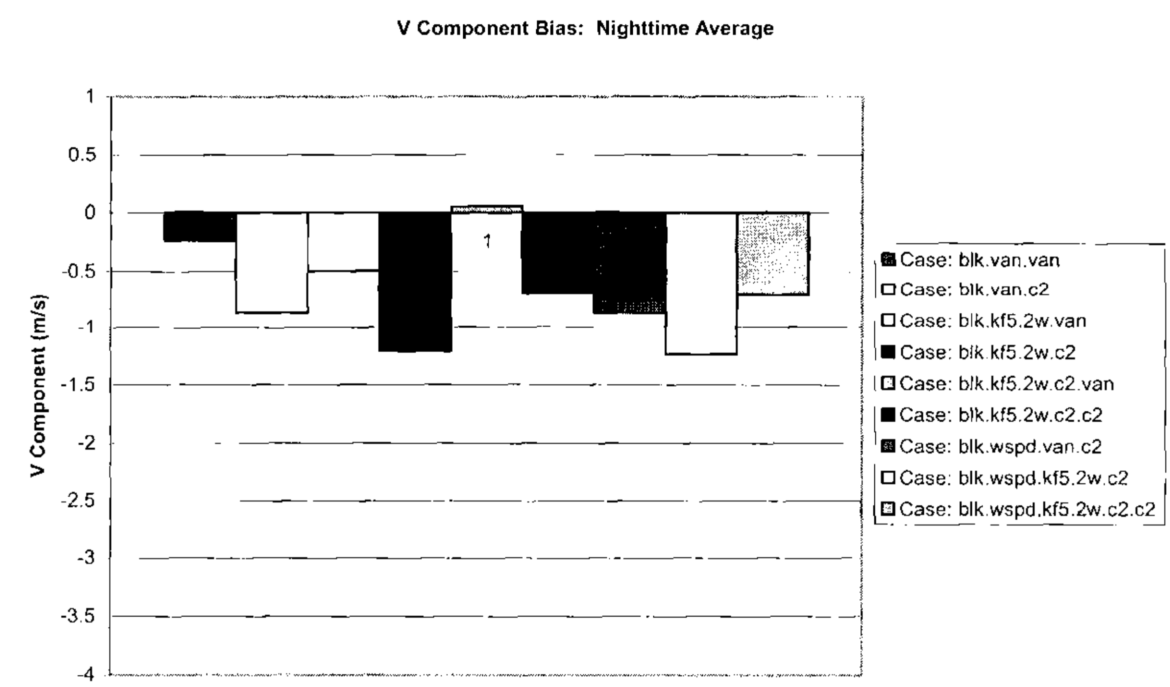


Figure 24. V-component wind bias at nighttime.

Other than the comparisons with station data screen-level variables, comparisons with GOES visible and IR data indicate superior performance in the coupled modeling system. For example, as shown in Figure 25 for August 25, 1998 at 1940UTC, the TOPLATS/MM5 results clearly resolve the daytime convective cloud development along the sea breeze convergence zone, as seen in the GOES imagery. The model results (also shown in Figure 25) demonstrate the impact of the cloud development on the 2-meter air temperature, and underscore the importance of the GOES radiation data used to force TOPLATS in these simulations.

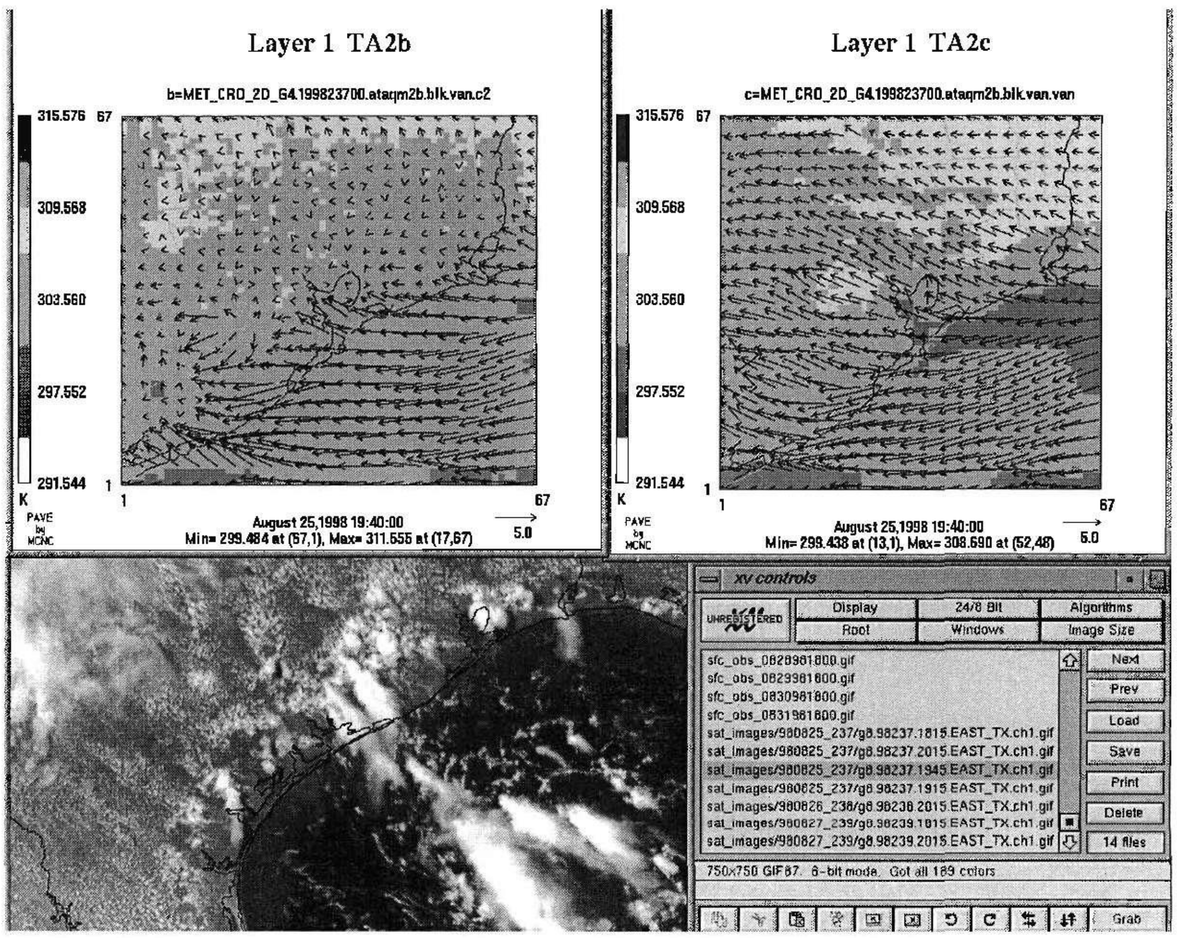


Figure 25. TOPLATS/MM5 (left) and SLAB/MM5 (right) modeled 2-m air temperature (TA2) and winds (vectors), along with GOES imagery verifying the formation of convective clouds along the sea breeze convergence zone.

In addition to the results in Figure 25, further results with TOPLATS underscore the importance of GOES radiation products in the coupled modeling system. Figures 26 and 27 illustrate differences in solar radiation from sparse surface observations, from MM5/SLAB simulations, and from GOES Surface Radiation Budget (SRB) products.

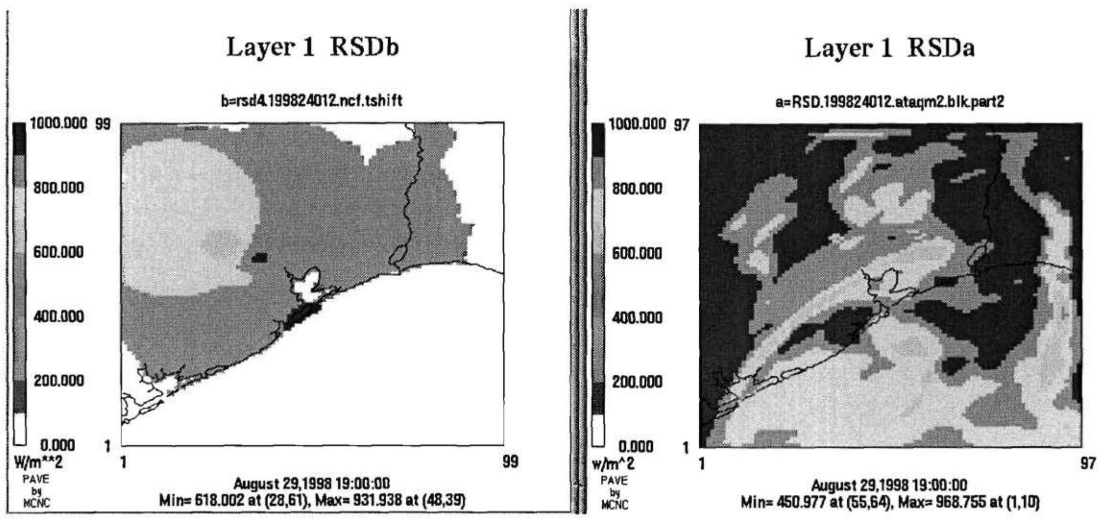


Figure 26. Downward surface flux of solar radiation (RSD) on August 29, 1998 at 19:00 Z from interpolated surface stations (LEFT) and as calculated by MM5v3.4 (RIGHT).

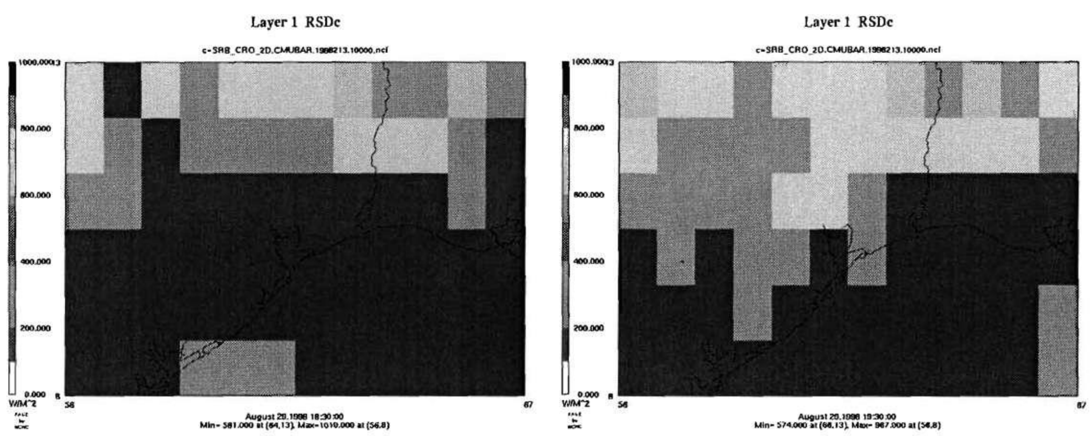


Figure 27. Downward surface flux of solar radiation (RSD) on August 29, 1998 from SRB data. Left figure shows hourly average from 18:00-19:00Z , and right figure shows hourly average from 19:00-20:00Z. Comparison with Figure 1 above demonstrates the potential for correcting surface flux biases caused by station data and/or MM5 output.

Figure 26 shows the downward surface flux of solar radiation (RSD) on August 29, 1998 at 19:00 Z from interpolated surface stations (LEFT) and as calculated by MM5v3.4 (RIGHT). This figure indicates upwards of 200 Wm^{-2} low biases in the station data in some locations. Overall, it is seen that the scarcity of stations with RSD measurements in the HGA domain leads to a nearly uniform interpolated field at locations far away from the stations. The MM5-calculated values on the right side of the figure show significant areas of lower radiation values associated with spurious clouds produced by the simulation. Of particular concern are the linear areas associated with clouds at the northern and eastern boundaries of the domain.

In contrast to Figure 26, Figure 27 shows the downward surface flux of solar radiation (RSD) from the SRB data on August 29, 1998. Because the surface flux data is given as hourly averages, we illustrate two time periods: from 18-19Z (LEFT) and from 19-20Z (RIGHT). A comparison of the two figures illustrates the following general conclusions about the SRB data: First, the native spatial resolution of the SRB data (approx. 0.5 deg) is coarser than MM5 (4 km), but able to resolve much more spatial detail than the available station data. Second, the values in and around Galveston Bay are generally 200-300 Wm^{-2} higher in the SRB data compared to the MM5 output due to the presence of spurious clouds in the MM5 simulation without TOPLATS. Finally, the low values observed at the station to the northwest of Houston are not verified by the SRB data, suggesting a problem with the station data.

5. Summary and Recommendations for Future Work

In accordance with the goals of the project, we have applied HPC parallel techniques to develop a coupled hydrological/meteorological modeling system capable of assimilating remotely sensed precipitation and radiation data. The HPC parallel techniques improve both the predictive capabilities and practical usability of the system, by allowing a fine scale surface hydrology model (Sparse-TOPLATS) to be coupled to a meso-scale meteorology model (MM5V3) to improve the representation of sub-grid scale heterogeneities that are responsible for significant errors in both model(s) and thereby reduce the uncertainties associated with using models for environmental risk assessments. Both inter and intra-program HPC parallel computational techniques have been incorporated to improve the approach to data assimilation and coupling of the models on temporal and spatial scales.

As described in Section 2, the design of the Sparse-TOPLATS model reduces simulations that once took approximately 5 hours to 5 minutes (on a single processor), by applying concepts of hydrologic similarity with appropriate discretization of topographic and meteorological inputs. Open-MP parallelism further reduces the execution time on shared memory multiprocessor systems. This design, in addition to a PVM-based "peer-to-peer" coupling strategy described in Section 3, allows for coupling models with disparate spatial and temporal discretizations, in three distinct modes: 1-way, 1.5-way, and 2-way. The 1- and 1.5-way modes are useful particularly for retrospective simulations in which all or part of the required data for one of the models is available from reliable sources, two of which might be NEXRAD precipitation data and GOES radiation data, as described in Section 4. Two-way coupling is required for forecasting applications, and is useful for examining feedbacks in the land-atmosphere system.

One-dimensional (1-D) coupled simulations described in Section 5 indicate that the coupling is important for atmospheric boundary layer development, although large-scale dynamics also play an important role. In Section 6, three-dimensional (3-D) coupled results for a large domain in the Houston-Galveston region indicate that high-resolution land surface modeling can be important for resolving complex urban heat island/sea breeze interactions, and that the assimilation of remotely sensed radiation is critical for accurate energy balance simulation.

A critical issue to be investigated in future work is the relative importance of differences in forcing (particularly downward shortwave radiation) versus differences in the land surface model physics, including the temporally and spatially varying soil moisture and temperature profiles in TOPLATS. Other important issues include the extension of the model coupling approaches developed as part of this work to coupling other environmental models, such as that envisioned for EPA's proposed Multimedia Integrated Modeling System (MIMS). Several proposals developed to extend the work towards this end were not funded, and therefore, there is currently no mechanism for extending the work into this area.

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Pan,F. and Peters-Lidard, C.D., 1999: The effects of flow direction and slope algorithms on TOPMODEL topographic index distribution and runoff prediction. *Presented at: American Geophysical Union Fall Meeting, December 13-17, 1999,San Francisco, CA.*

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Peters-Lidard, C. D., J. N. McHenry, C. J. Coats, Jr., and A. Trayanov, 2002: Coupling Land Surface and Atmospheric Models Based on Hydrometeorological Similarity. *Manuscript in preparation for Journal of Hydrometeorology.*

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Peters-Lidard, C. D., J. N. McHenry, C. J. Coats, A. Trayanov, S. Fine, K. Alapaty, and F. Pan, 1999: Re-Thinking the Atmospheric LSP Problem from a Hydrological Perspective. *Preprint volume: 14th Conference on Hydrology, American Meteorological Society, Dallas, Texas.*

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8. Publications and Presentations Resulting from Grant

8.1 Publications

Peters-Lidard, C. D., J. N. McHenry, C. J. Coats, Jr., and A. Trayanov, 2002: Coupling Land Surface and Atmospheric Models Based on Hydrometeorological Similarity. *Manuscript in preparation for Journal of Hydrometeorology.*

Peters-Lidard, C. D., C. J. Coats, Jr., J. N. McHenry, and A. Trayanov, 2002: High Performance Parallel Coupled Land Surface-Atmosphere Modelling. *Manuscript in preparation for Environmental Modelling & Software.*

8.2 Presentations

Coats, C. J., Jr., A. Trayanov, J. N. McHenry, A. Xiu, A. Gibbs-Lario, and C. D. Peters-Lidard, 1999: An Extension of the EDSS/Models-3 I/O API for Coupling Concurrent Environmental Models, with Applications to Air Quality and Hydrology, Paper J10.6, *Preprint volume: 14th Conference on Hydrology, American Meteorological Society, Dallas, Texas.*

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Peters-Lidard, C.D., L. H. Davis, J. N. McHenry, and Pan, F., 2000: Observed and modeled properties of the atmospheric boundary layer during SGP97. *Presented at: 15th Conference on Hyrdology, American Meteorological Society, January 9-14, 2000, Long Beach, CA.*

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9. Students Funded by Grant

- Mr. Feifei Pan, Ph.D. Candidate, Georgia Tech, School of Civil and Environmental Engineering, April 2002.
- Mr. Brian Keel, MSCE, Georgia Tech, School of Civil and Environmental Engineering, August 2001.
- Mr. Adam Stewart, MSCE, Georgia Tech, School of Civil and Environmental Engineering, December 2001.